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MECHANISTIC MODELING OF RUNOUT, OVALITY AND MISALIGNMENT IN REAMING PROCESS

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ABSTRACT

Common process faults during reaming operations are runout, ovality and misalignment which leads to an increase in dynamic cutting forces during the reaming operation. This paper presents computation of cutting forces through the mechanistic modeling with process faults. Simulated results and experimental results were obtained for different materials and presented in the paper. For the experimentally obtained dynamic forces, process faults were manually given on the workpiece and dynamic forces were obtained. The Deckel Maho milling machine and kistler dynamometer are used for experimental work.

KEYWORDS: Mechanistic Model, Process Faults, Reaming, Simulation & Dynamic Force

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Original Article

INTRODUCTION

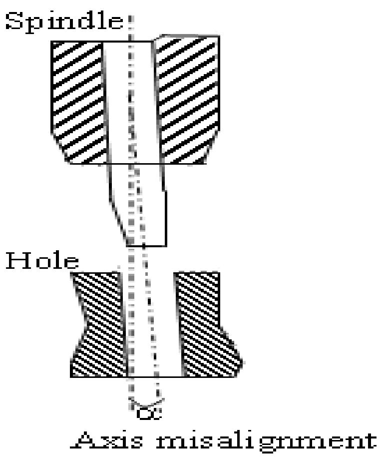
Axis misalignment is a frequently appearing process fault in a reaming process. This fault is due to misalignment of the axis of the drilled hole with the axis of the spindle. Usual assumption for reaming is that reamer and axis of the spindle are aligned, but in reality there exists a tilt between hole axis and reamer axis due to misalignment. Run out of reamer is a process fault occurring due the presence of offset between reamer axis and spindle axis. There is an assumption that hole and spindle axis are aligned, but in reality they are not aligned in the presence of run out. Once reamer proceeds inside the drilled hole, the cutting edges on either side of the tool axis will experience variation in the chip load. This variation in chip load will result in increase of reaming torque in a stepped manner until reamer completely engage with the work piece. In an ideal situation, when reamer and work piece are fully engaged chip load variation is negligible and value reaches a steady state. In this state, rotation of the reamer rotation will not have any affect the chip load. Due to this, cutting force will not have a dynamic component. However, the round hole obtained will not conform to what is expected in an ideal case. The prominent cutting edges of the reamer will be subjected to higher chip load due to the presence run out. This will result in uneven wear and subsequently chipping of the tooth and finally breakage. During reaming operation, base holes are drilled according to the size of the reamer used. The errors in the drilling machine tool and drill bit due to axis misalignment and eccentricity can produce ovality in the drilled hole. Ovality may be considered as eccentricity which is equal to the axial shift between the reamer and hole axis.

BACKGROUND

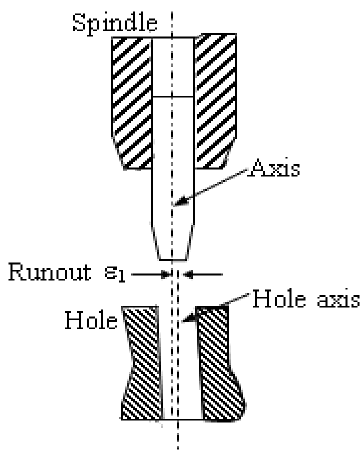
The Merchant cutting force model presented in 1945 (Merchant, 1945) applicable to both turning and drilling. The model showed that cutting force was proportional to the uncut chip area or the chip load. Afterwards,

most of the work was related to the drilling operation with different tool geometry and cutting process parameters. The lobbing in reamed holes was examined and reported that the problems of reaming faults was mainly due to uneven pitch of reamer flutes (Friedman et. al, 1974). The accuracy of hole obtained by multifluted carbide reamer was experimentally investigated (Sakuma et. al, 1986). They have made an attempt to illustrate the related reamer dynamics leading to the generation of lobbed holes. The study also highlighted the various critical factors effecting the final quality of the reamed hole. Further, a quasi-static model of reaming was developed to study the lobbing pattern in a reamed holes (Bayly et. al, 2001). A simulation model was developed for drilling and reaming process and it can predict the dynamic forces as chatter limit based on feed and point of angle (Yang et. al 2002). Another model developed was a mechanistic model for reaming process with emphasis on process faults (Bhattacharya et. al, 2005). Research has been carried out to develop a mechanistic model for variety of machining processes such as drilling, face milling, tapping, end milling (Oxford, 1976; Kim et. al, 1993).

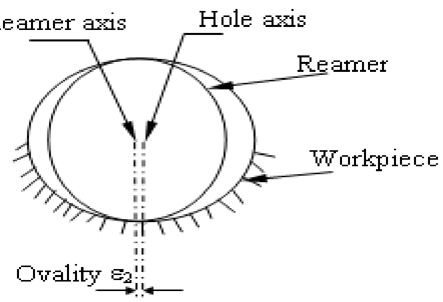
One of the first analytical formulations of the dynamic cutting force variation due to chip thickness variation, the rate of penetration and the cutter velocity were established in early sixties(Tobias et. al, 1965). The drilled hole obtained being not perfect, chip load is calculated as interference area of tool and work piece which is not deformed as function of time [Surendran, 1998; Jayram et. al, 2001). The specific energy constants due to chip load are based on material of the tool and workpiece, cutting speed range, chip thickness and are independent of the machining process (Meriritt, 1965). Mechanistic force models are formulated on following assumptions, Static cutting forces begin to excite the stationary reaming machine and dynamic cutting force is generated by regenerative vibration (Jayram et. al, 2001).



(a) Axis Misalignment



(b) Reamer Runout



(c) Ovality

Figure 1: Process Faults in Reaming

In this paper simulation of cutting forces during reaming operations are presented considering the misalignment, run out and ovality. The paper also reports experimentally obtained cutting forces due to the above mentioned faults. In this case a 15 mm reamer is used in a 14.5 mm drilled hole to demonstrate the estimation of cutting forces during the reaming operation.

Figure 1 illustrates reamer run out, axis misalignment and ovality. The presence of run out, axis misalignment and ovality can change radius of the hole for different degree of rotation from the axis of the reamer. As a result, chip load and cutting forces are greatly affected. The mechanistic model for estimating specific cutting pressure for mechanistic cutting force models (Jayram et. al, 2001) can be appropriately modified for reaming operation considering the variation in chip load area and centroid distance. Auto CAD drawings of the reamer with appropriate coordinate is used to compute chip load area and centroidal distances. The effect of misalignment, run out and ovality produces an altered hole profile and reamer coordinate system assist in predicting the reaming force due to misalignment, run out and ovality due to chip load and centroidal distances.

RUNOUT

In the case of reamer run out, assumption is that reamer axis undergoes an offset parallel to the spindle axis. The tolerance class according to the ANSI/ASME B1 standard of 1995 for internal reaming is illustrated in Figure 2 (Bhattacharya et. al, 2005). The variation of the tolerance causes the centre of reamer to rotate around spindle centre with a radius same as amount of run out. This results in reamer cutting uniformly deeper along circumference of the hole. This gives rise to large depth of hole everywhere around the hole. The thickness of the chip removal is constant for no fault case is,

$$h = (D - D_1)/2 \tag{1}$$

where, D is the maximum hole diameter andD_1 is the drilled hole diameter.

For run out fault, chip thickness h is constant and is,

$$h = [(D - D_1)/2] + \varepsilon_1 \tag{2}$$

where, ε_1 is magnitude of run out.

The uniform increase in chip thickness results in increase of effective diameter of the hole D_2 to increase, which is given as,

$$D_2 = D_2^{BS} + 2\varepsilon_1 \tag{3}$$

where, D_2^{BS} is the basic size effective hole diameter as per the standard of reaming operation.

The value of effective diameter of the should lie in the tolerance range specified in order to get a correct fit for the shaft. The hole diameter will be inside the allowable tolerance range, when total of tolerance and lower deviation is always greater than run out.

$$\varepsilon_1 \leq \frac{\mathrm{LD}(\mathrm{D}_2) + \mathrm{T}(\mathrm{D}_2)}{2} \tag{4}$$

where, LD (D_2) represents deviation at the lower end for the basic size effective hole diameter for the specified tolerance position and T (D_2) is the tolerance grade for the basic size effective hole diameter.

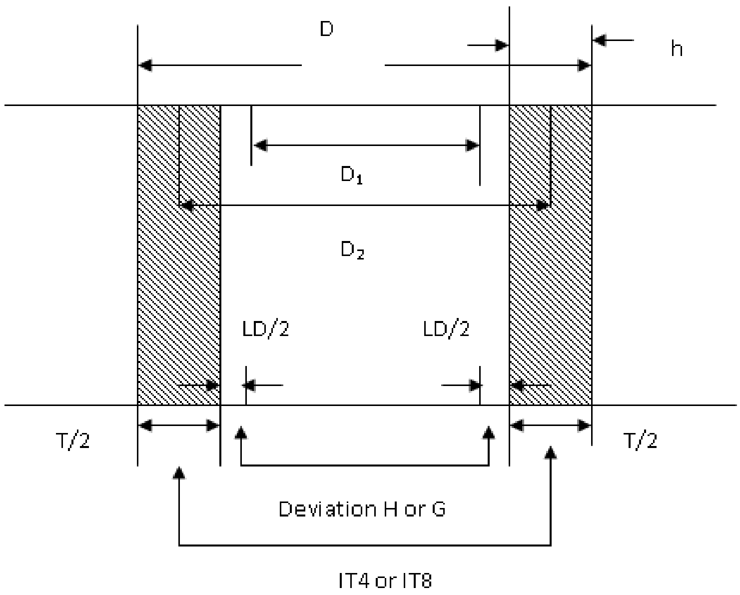


Figure 2: Tolerance Class for a Reamer

It has been observed that there is a linear relationship between the amount of reamer run out and increase in the magnitude of dynamic forces compared to the condition without run out. The proportionality constant C_R can be used to estimate measured forces in radial direction. C_R is dependent on conditions used during cutting and work piece material. The peak to valley magnitude of dynamic forces in radial direction due to run out can be computed as (Kline et. al, 1983),

$$\varepsilon_1 = C_R\left(\left|dF_R\right| - \left|dF_R(no\ \ fault)\right|\right) \tag{5}$$

The constant of proportionality C_R can be determined through experiments or mechanistic dynamic force model. The average radial force during reamng for no fault and with run out is zero, hence couple of simulations of reaming using mechanistic model of reaming can be used to compute C_R. For a particular cutting condition and work piece, C_R may be constant.

$$C_R = \frac{\overline{\varepsilon_1}}{\left|dF_R\right| - \left|dF_R(no\ \ fault)\right|} \tag{6}$$

where, $\overline{\varepsilon_1}$ is the magnitude of simulated or experimental run out, dF_R and dF_R(no-fault) are the magnitudes of simulated or experimental radial force with and without faults. The value of C_R is determined from simulated force values and the value of C_R for selected materials is shown in Table 1. For simulation, the drilled hole diameter D is 14.5 mm and IT 7 tolerance values are used for different materials.

Table 1: C_R for the Selected Materials

Material	Reamer Size	Drill Size (Mm)	Cutting Speed (Rpm)	Reamer Run Out (Mm)	Df_r without Run Out (N)	Df_r with Run Out (N)	C_R (Mm/N)
Cast Iron	15 mm	14.5	400	0.08	25.6	36.0	0.0076
Mild Steel				0.08	27.4	38.2	0.0074
Aluminium				0.08	18	29.5	0.0069

OVALITY

Ovality can be shown to have the same effect as eccentricity. The axial shift due to ovality is given as ε_2. In the case of ovality, assumption is that there exists an offset between axis of the reamer and work piece axis. The magnitude of ovality results in variable radius with which centre of reamer rotates around centre of the spindle. This further results reamer cutting deeper uniformly along the circumference of the hole. In other words, larger depth of material will be removed where ovality is maximum. In the absence of the above fault, height will be constant as given in Equation (1).

For ovality, the chip thickness, h is constant hole height is equal to,

$$h = ((D - D_1)/2) + \varepsilon_2 \tag{7}$$

where ε_2 is the magnitude of maximum ovality.

In the similar line as explained in the case of run out, it has been observed that there is a linear relationship between the amount of reamer ovality and increase in the magnitude of dynamic forces compared to the condition without ovality. The proportionality constant C_O can be used to estimate measured forces in radial direction. C_O is dependent on conditions used during cutting and work piece material. The peak to valley magnitude of dynamic forces in radial direction due to ovality can be computed as,

$$\varepsilon_2 = C_o\left(\left|dF_R{}'\right| - \left|dF_R{}'(no\ fault)\right|\right) \tag{8}$$

The coefficient of proportionality C_o can be determined through experiments or simulated dynamic force results. It is computed as given in equation (9).

$$C_o = \frac{\overline{\varepsilon_2}}{\left|dF_R{}'\right| - \left|dF_R{}'(no\ fault)\right|} \tag{9}$$

where, $\overline{\varepsilon_2}$ is the magnitude of simulated or experimental mode ovality, dF_R' and$dF_R{}'$(no-fault) are the magnitudes of simulated or experimental radial force with and without faults. The value of C_o is determined both experimentally as well as simulated. The value of C_o for selected materials is shown in Table 1 which is same as the case of the run out. The parameters used for the estimate of the C_o for ovality is same as in the case of run out.

AXIS MISALIGNMENT

The misalignment of reamer axis takes place whenever reamer axis is not aligned with hole axis. Figure 3 illustrates the uneven depth of cut due to axis misalignment A vector is defined in a x-y coordinate space to represent altered position of the spindle axis A. The centre of the hole is located at O. Let h(α) be the chip thickness variation due to axis misalignment.

Then, h(α) can be found from Figure 3 as:

$$h(\alpha) = (X_Y \cos\alpha + Y_X \sin\alpha) + \sqrt{(X_Y \cos\alpha + Y_X \sin\alpha)^2 - a_0{}^2 + \left(\frac{D}{2}\right)^2} - \frac{D_1}{2} \tag{10}$$

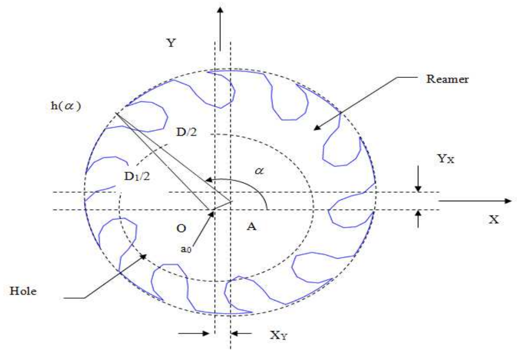


Figure 3: Calculation of Chip Thickness along hole Circumference with Axis Misalignment

Where α is the angle of rotation of the reamer, X_Y and Y_X are the axis shift in x and y direction respectively due to misalignment.

The hole cutting chip thickness varies around the hole due to axis misalignment hole effective diameter does not change. There will be a shift in the hole with respect to position of hole, leaving maximum diameter unchanged. However, the hole shifting can cause serious quality problems by resulting in an interference fit when the internal shaft is engaged by a hole.

The value of axis misalignment can be estimated by knowing cutting paramters and simulated values of average forces in radial direction. Average of force along x-axis is proportional to offset of the axis in Y direction and average of the forces along Y-axis is linearly proportional offset of the axis in X-direction. The steady-state cutting force Fx' and FY' corresponding to Y axis and X axis shift from the dynamic forces of the simulated or experimental results can be obtained, from which one can determine the magnitude of misalignment. The Fx' and FY' are the components of the radial force in x and y direction and Xy and Yx be the magnitudes of misalignments in the X and Y directions which is equal to,

$$\mathrm{Xy} = C_A F_y{}'$$

$$\mathrm{Yx} = C_A \mathrm{F_x}{}' \tag{11}$$

where, C_A is the constant of proportionality that depends on conditions during cutting and type of work piece material. The C_A may be found through mechanistic reaming model or from the experimental results. If the measurement or simulation of the axis mis-alignment is only in Y- axis, then the x-axis force will show the shift in mean. Computation of C_A involves conducting a single simulation or experiment for a set of given parameters of cutting, i. e.

$$C_A = \frac{Y_X}{\mu \bar{F}_X} \tag{12}$$

where, Y_x represents amount of axis misalignment, μ is defined as elasto modulus of rigidity which is equal to 0.8 x 10^5 N/mm^2 and $\overline{F}_X$ represents average of the simulated values of force radial direction during steady-state machining. Table 2 gives the computed values of C_A for different materials.

Table 2: 'C$_A$' Values for the Work Material Selected

Material	Reamer Size	Drill Size (mm)	Cutting Speed (rpm)	Axis Misalignment Y_x (mm)	$\overline{F}_X$ (N)	$\overline{F}_Y$ (N)	C_A (mm/N)
Cast Iron	15 mm	14.5	400	0.03	46.8	0	0.00064
Mild Steel				0.03	54.2	0	0.00055
Aluminium				0.03	29	0	0.00103

EXPERIMENTAL RESULTS

Figure 4 shows the tangential cutting force spectrum obtained through reaming of mild steel work piece with 15 mm reamer and experimentally set run out of 0.01 mm. Because of the run out the amplitude of the dynamic force is increased. In each cycle of cutting, there are over shoot and under shoot indicating cutting action of the reamer. The maximum dynamic cutting force without run out is 33.3 N for 15 mm reamer for mild steel work piece. It is noted that tangential cutting force is equal to torque divided by the radius of the reamer. With a run out of 0.01 mm, cutting force has increased to 40 N and hence there is increase in the cutting force by 20 percent. For different reamer sizes, of sizes 15 mm, 20 mm and 24 mm and work materials, mild steel, aluminium and cast iron, the pattern of the cutting force spectrum is same. However, at speed of 700 rpm the cutting force spectrum is erroneous or random in nature indicating tool chatter as shown in figure 5. In the case of tool chatter, the dynamic force value is same as at 400 rpm. The Deckel Maho universal milling and drilling machine with kistler three component dynamo meter are used for the experimental work.

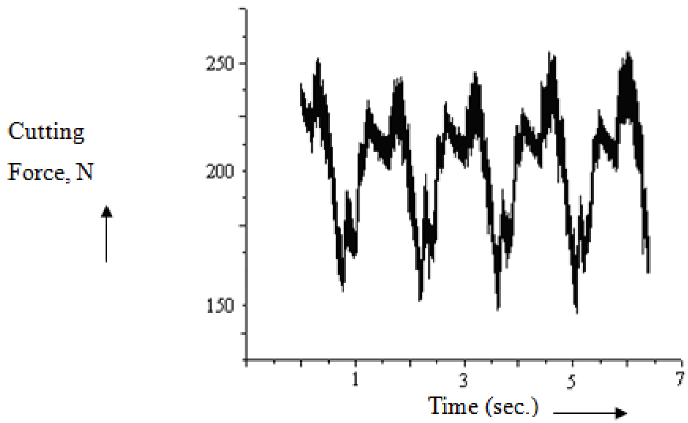


Figure 4: Experimentally Obtained Force Spectrum in X Direction with a Run Out0.01 Mm for a 15 Mm Reamer for Mild Steel Work Piece

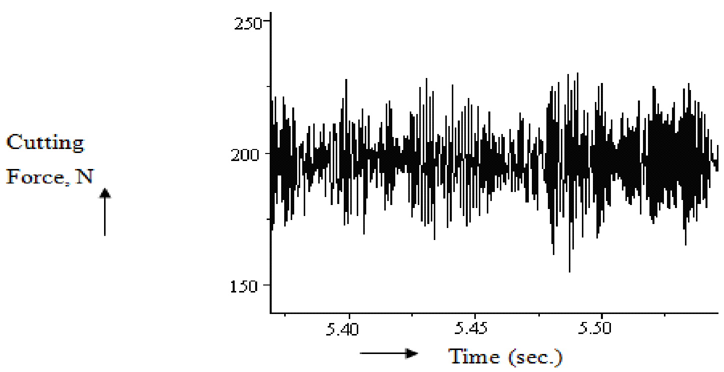


Figure 5: Experimentally Obtained Force Spectrum in X Direction for a 15 mm Reamer at 700 Rpm for Mild Steel Work piece

CONCLUSIONS

The cutting force analysis on reaming operation with process faults such as run out, ovality and misalignment were estimated through mechanistic modeling and obtained through experimental work. Dynamic cutting forces due to the process faults were obtained for different materials namely mild steel, aluminium and cast iron respectively. For a reamer of size 15 mm with drilled hole of size 14.5 mm and for the run out or ovality of 0.01mm, there is a 30% of increase in the cutting force and it is observed that dynamic force with fault run out or ovality is 36N. Experimentally it is observed that there is 20% increase in the cutting force with 0.01mm run out and cutting force with fault is 40N. Cutting force results are also simulated with misalignment through mechanistic model.

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